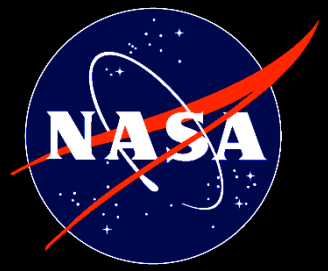


ExoPAG SAG13: Exoplanet Occurrence Rates and Distributions

Ruslan Belikov
NASA Ames Research Center
on behalf of SAG13

SAG13 members

Belikov, Ruslan (Chair, rulsan.belikov@nasa.gov)
Stark, Christopher (Co-chair)
Batalha, Natalie (Steering Committee)
Burke, Chris (Steering Committee)

Angerhausen, Daniel
Apai, Daniel
Bendek, Eduardo
Bennett, David
Blackwood, Gary
Boss, Alan
Brown, Robert
Bryden, Geoff
Cahoy, Kerri
Catanzarite, Joe
Ciardi, David
Clanton, Christian
Cowan, Nick
Danchi, William
Domagal-Goldman, Shawn
Dressing, Courtney
Farr, Will
Foreman-Mackey, Daniel
Fressin, Francois
Gaudi, Scott
Ge, Jian
Gould, Andy
Hogg, David W
Howard, Andrew
Kane, Stephen
Kasting, Jim
Kopparapu, Ravi
Macintosh, Bruce
Mandell, Avi
Mendez, Abel
Meyer, Michael
Morgan, Rhonda
Mulders, Gijs
Nielsen, Eric
Petigura, Erik
Ragozzine, Darin
Roberge, Aki
Rogers, Leslie
Savransky, Dmitry
Serabyn, Gene
Shabram, Megan
Shao, Mike
Solmaz, Arif
Sparks, William
Stahl, Philip
Stapelfeldt, Karl
Stark, Christopher
Still, Martin
Suzuki, Daisuke
Swain, Mark
Traub, Wes
Turnbull, Margaret
Unwin, Stephen
Vanderbei, Bob
Walkowicz, Luzianne
Weiss, Lauren M.
Wolfgang, Angie
Youdin, Andrew

Charter

Over 5000 exoplanets and exoplanet candidates have been discovered to date. Many studies have been published and are on-going to determine exoplanet occurrence rates and distributions, particularly for potentially habitable worlds. These studies employ different statistical and debiasing methods, different definitions of terms such as eta_Earth and habitable zone, different degrees of extrapolation, and present distributions in different units from each other. The primary goal of this SAG is to evaluate what we currently know about planet occurrence rates, and especially eta_Earth, by consolidating, comparing, and reconciling discrepancies between different studies. A secondary goal is to establish a standard set of occurrence rates accepted by as much of our community as possible to be used for mission yield estimates for missions to be considered by the decadal survey.

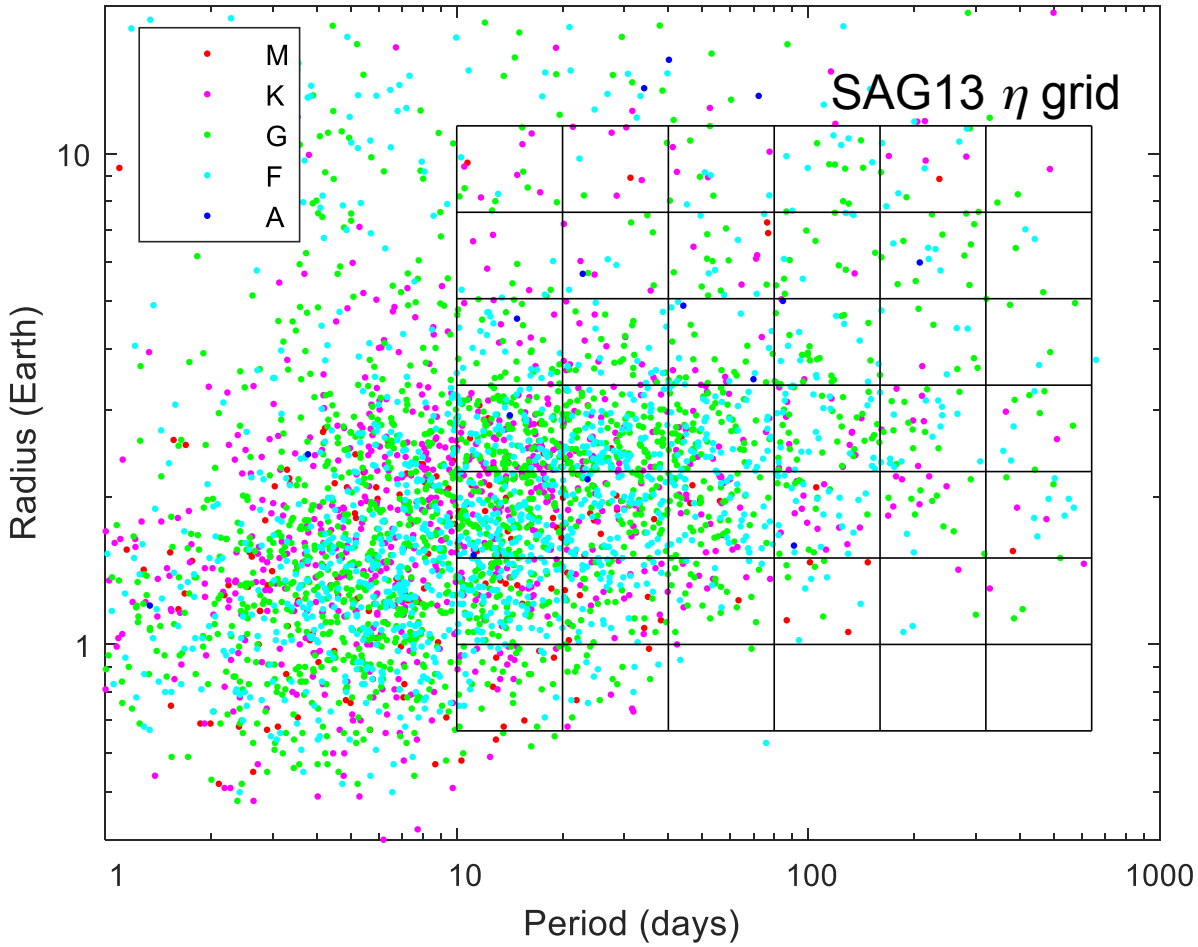
Key objectives and questions:

Completed →
1. Propose standard nominal conventions, definitions, and units for occurrence rates/ distributions to facilitate comparisons between different studies.

Current activity →
2. Do occurrence estimates from different teams/methods agree with each other to within statistical uncertainty? If not, why?

Current activity →
3. For occurrence rates where extrapolation is still necessary, what values should the community adopt as standard conventions for mission yield estimates?

Standardized eta grid



11 community sourced occurrence tables

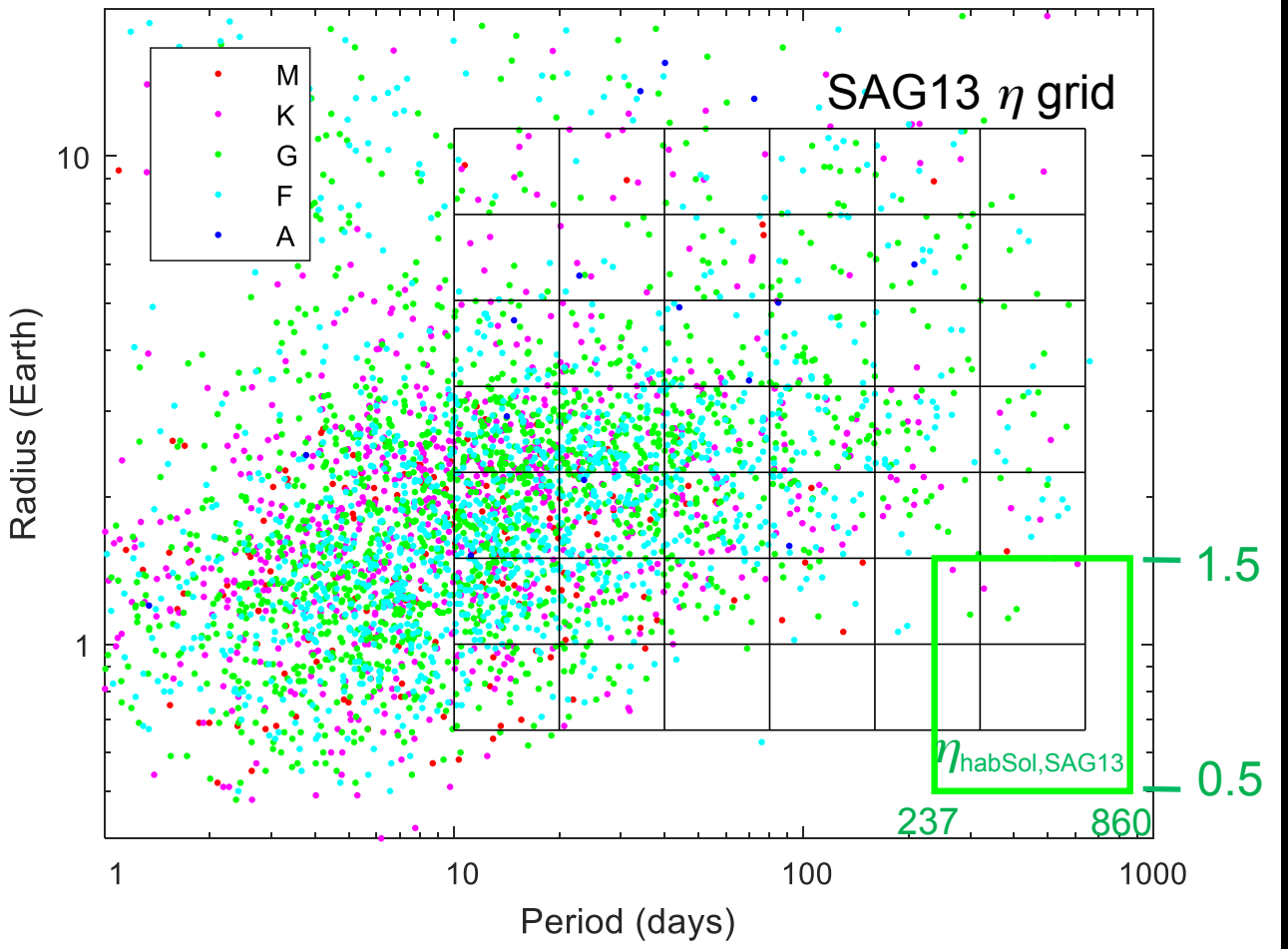
Batalha, Natalie (2)
Belikov, Rus
Burke, Chris
Catanzarite, Joe
Dressing, Courtney*
Farr, Will
Foreman-Mackey, Daniel*
Kopparapu, Ravi
Mulders, Gijs
Petigura, Erik*
Traub, Wes**

*dataset was based on prior publications and re-integrated across SAG13 bins by Burke
** expected soon

All datasets and documents can be found on SAG13 repository: https://drive.google.com/drive/folders/0B520NCfkP4aOQUJYdmUzQTJkdkE

- Dots are an example catalog: Kepler candidates from Q1-Q17, dr24
  - SAG participants are free to choose any catalog and method

Standardized eta grid



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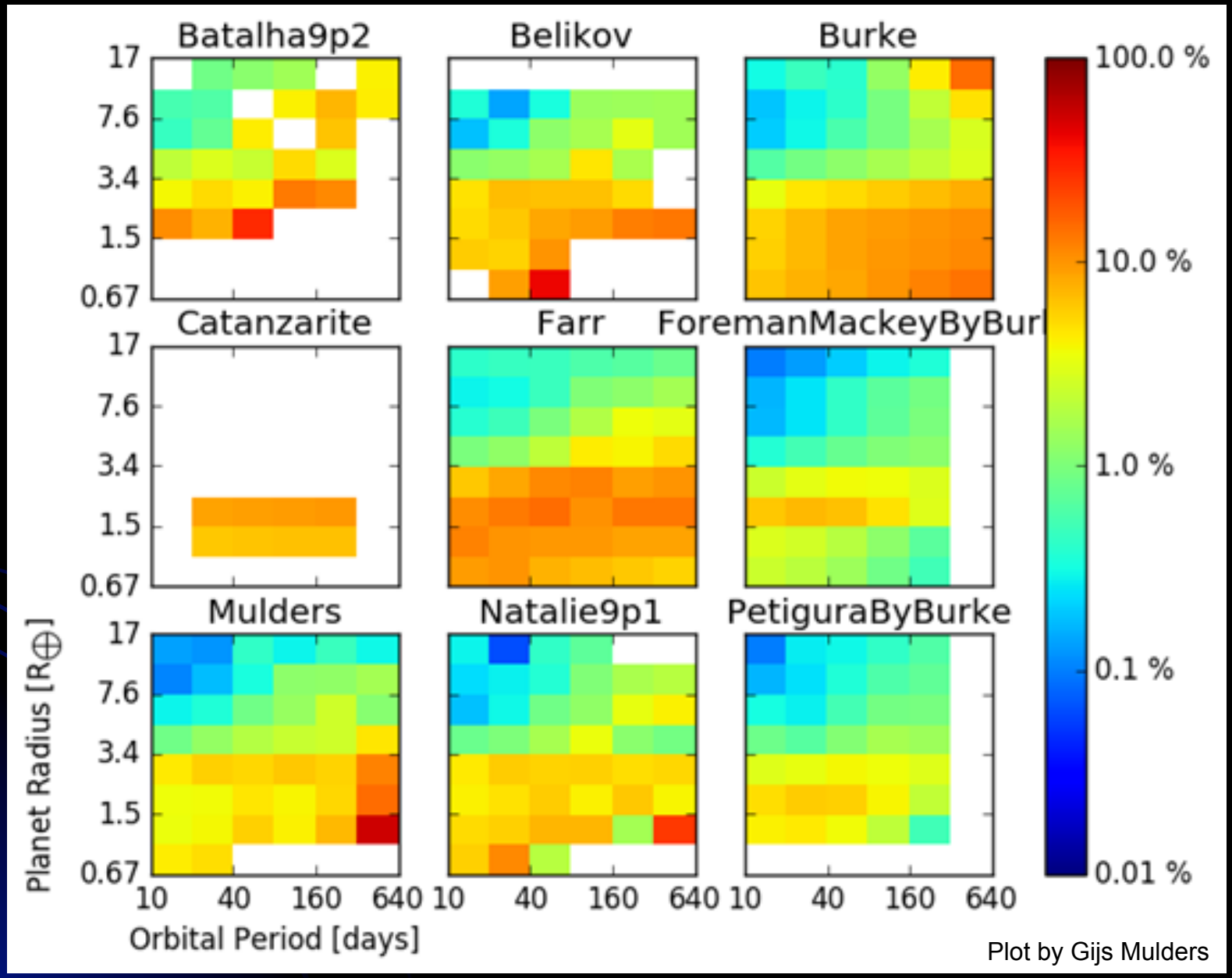
- $\eta_{habSol,SAG13}$
  - R = [0.5 – 1.5], P = [237 860] (Kopparapu extended HZ for Sol twin)
  - This is not exactly η_{Earth} , just a tentative rough representation of a potentially habitable region

Example: submitted occurrence rates for G-dwarfs



Plot by Gijs Mulders

How do we combine different submissions into one occurrence table?

Full accounting:
Only "independent" submissions are averaged

Accounting for "dependency" between submissions

No accounting:
Simply average all submissions

- Best for producing an actual scientific measurement
- Measuring "dependency" is not trivial (and may be impossible in principle)
- Consensus on method can be challenging
- Psychological biases are challenging to identify and control

- Will not generate a scientific measurement, but possibly best for predictions?
- Simple method
- Easier consensus: all submissions are automatically fairly represented
- Crowdsourcing / Prediction market philosophy: psychological biases are in theory averaged out

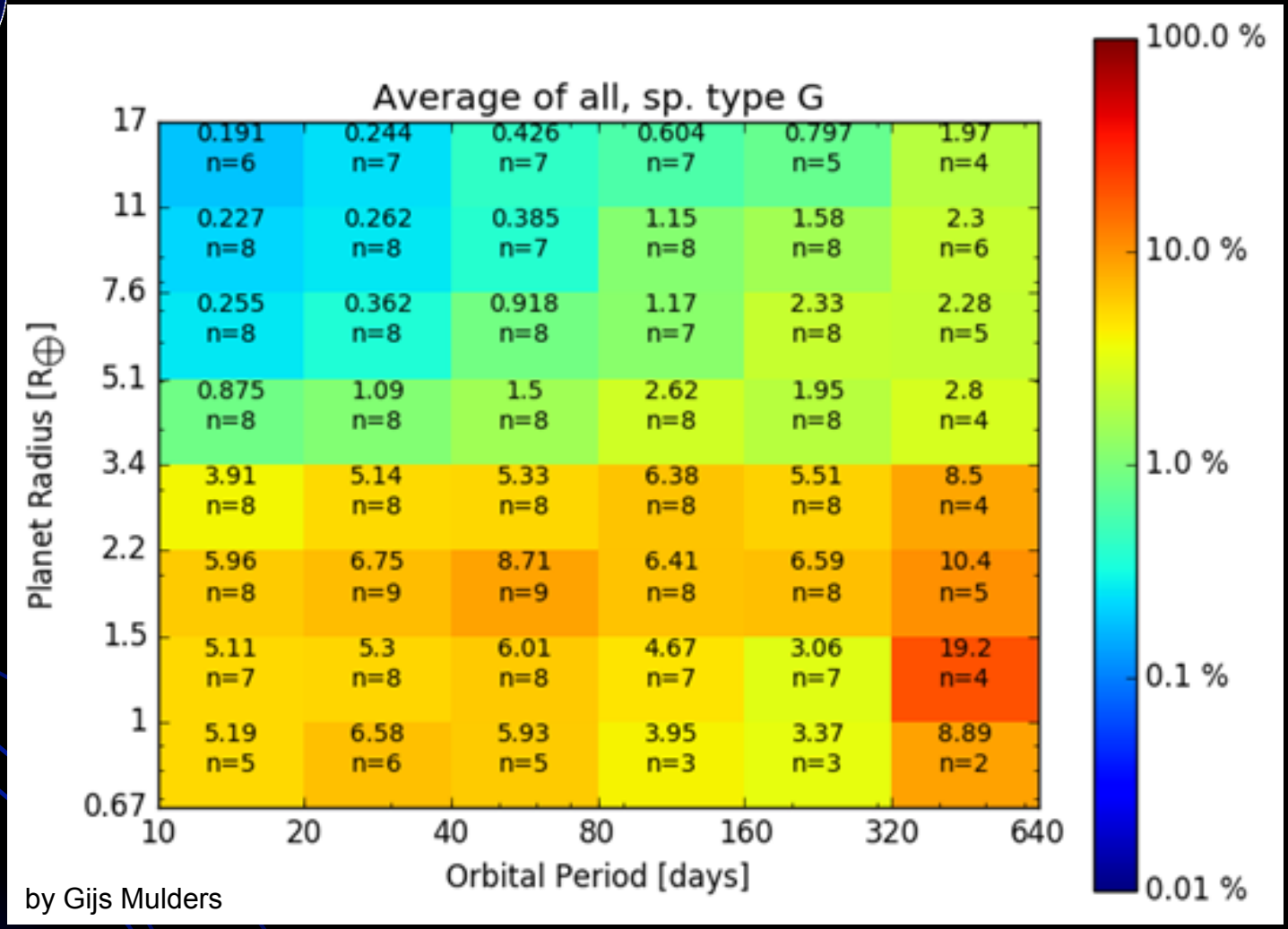
The question of which method is "correct" is possibly philosophical
Will probably do both, explicitly describe the process, and leave interpretation to the reader
Feedback on our strategy is welcome and encouraged

Closer look at G-dwarf average

legend

% occurrence

# of submissions



by Gijs Mulders

Closer look at G-dwarf average

legend

% occurrence

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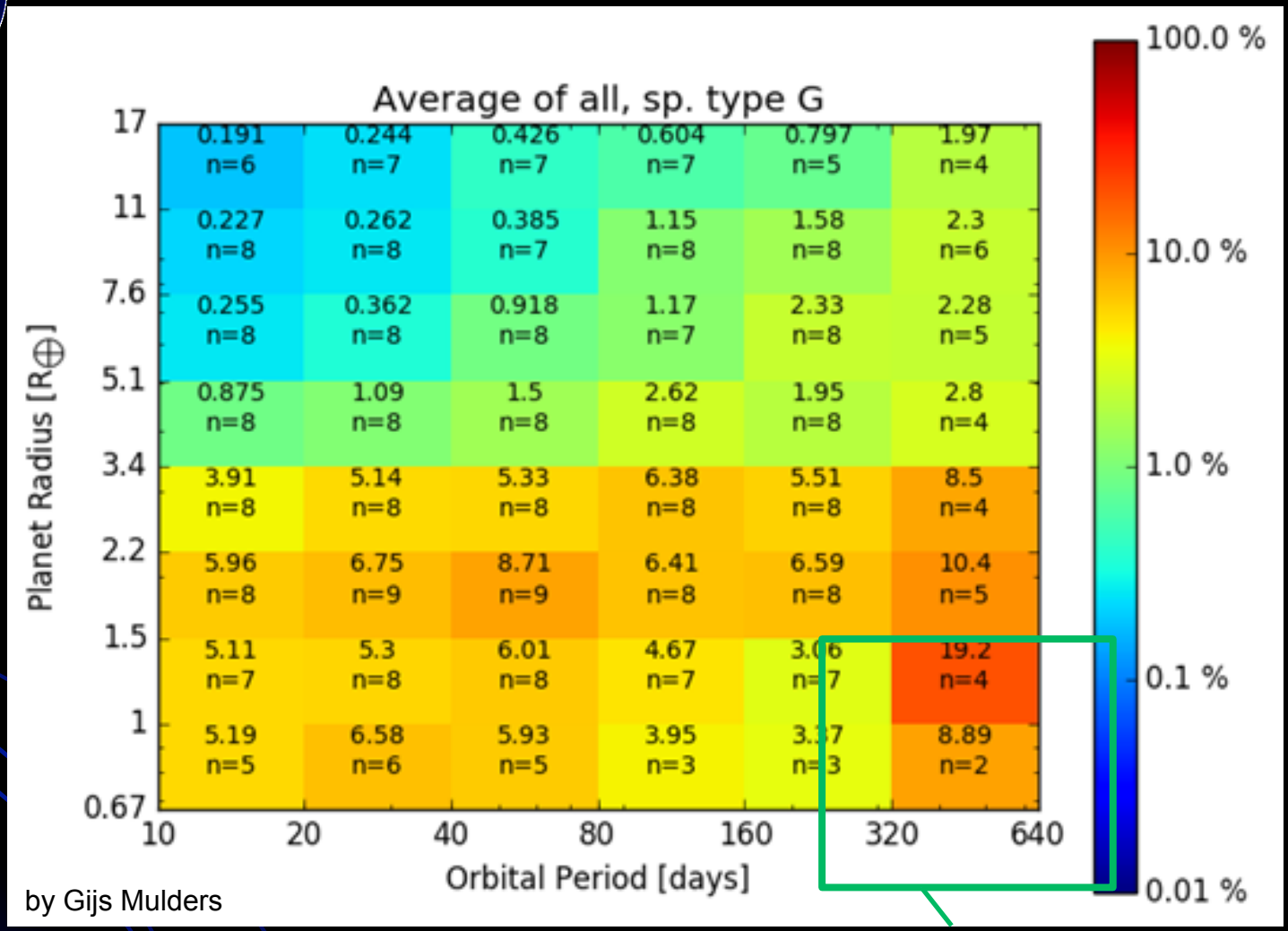
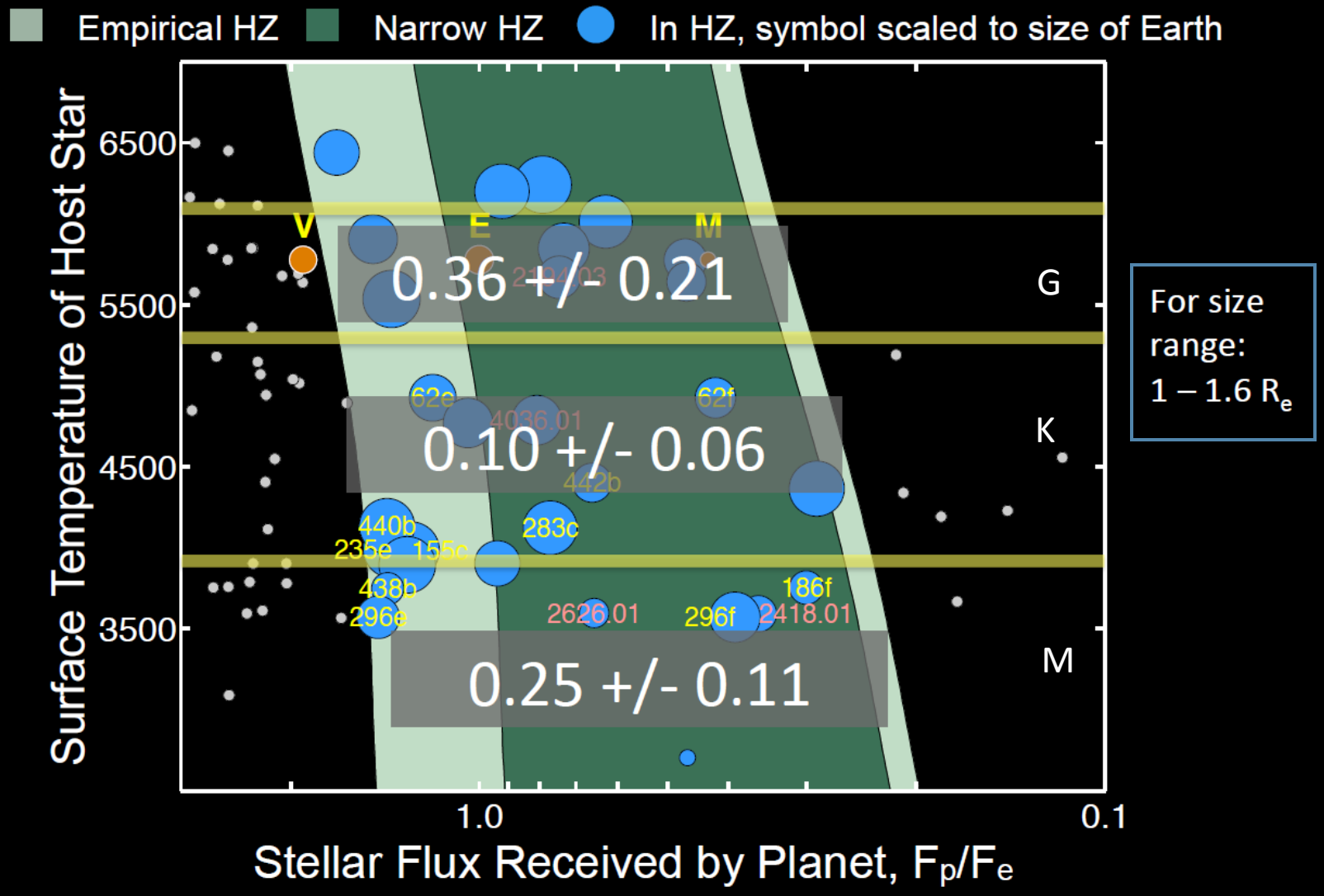


by Gijs Mulders

Average occurrence per SAG13 bin in green box: ~10%
Area of green box: 5x SAG13 bins
Uniform extrapolation implies green box occurrence of **50%**
Note: this number is *not* an official SAG13 value for $\eta_{\mathrm{habSol,SAG13}}$, it is just an example of a simple extrapolation.

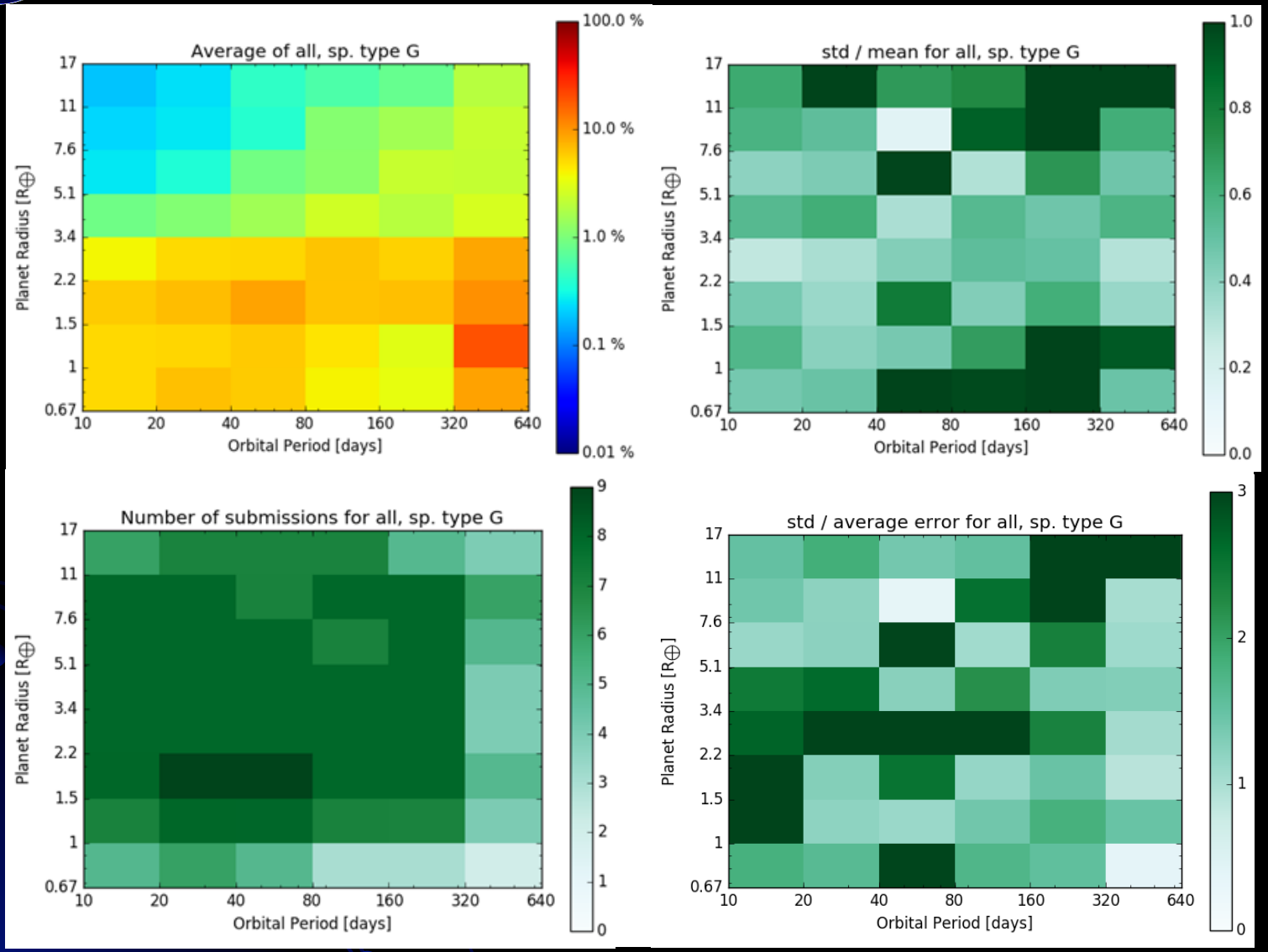
Courtesy of Natalie Batalha

Small (< 2 R_e) Planets in the HZ: 4 yr



Note: for planet size range of 0.5 – 1.6 R_e , expected # of planets may be a factor of ~2-3 higher
(based on extrapolation)

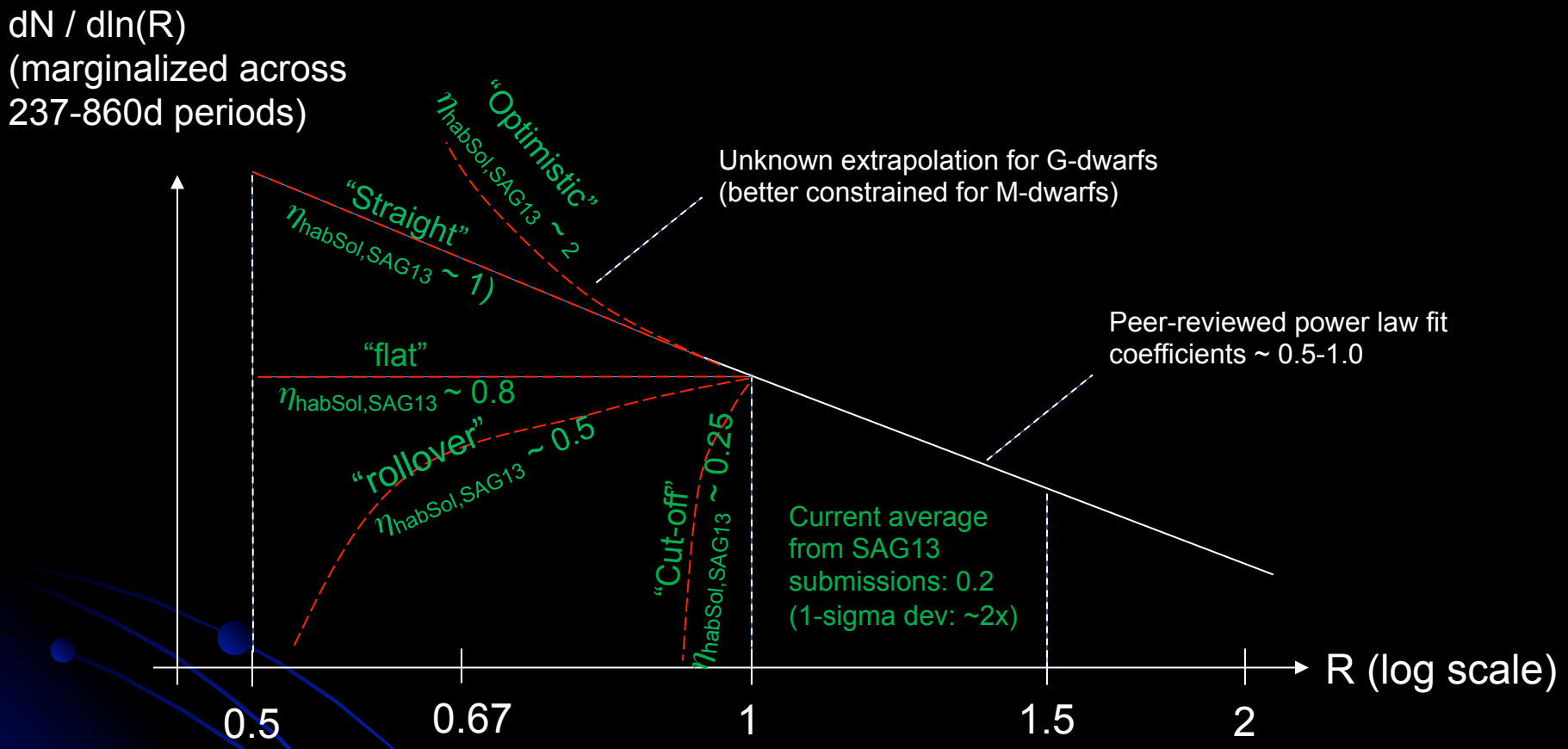
Analysis of variations in submissions (for G-dwarfs)



Crowdsourced standard deviation normalized to submitted occurrence uncertainty

by Gijs Mulders

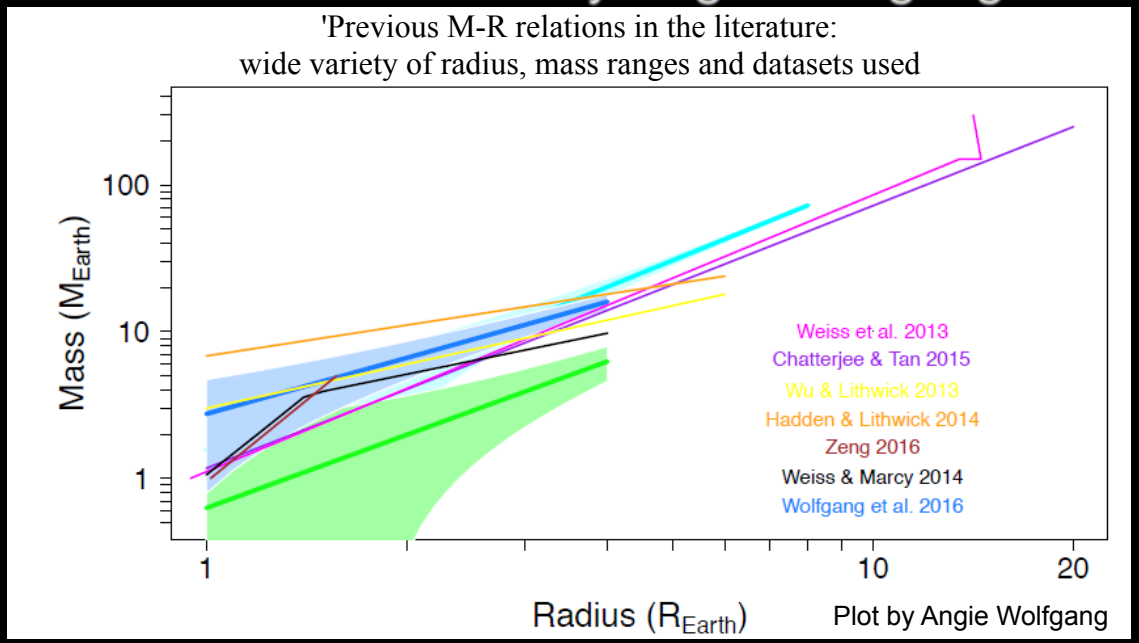
Importance of 0.5-1.0 Earth size bin

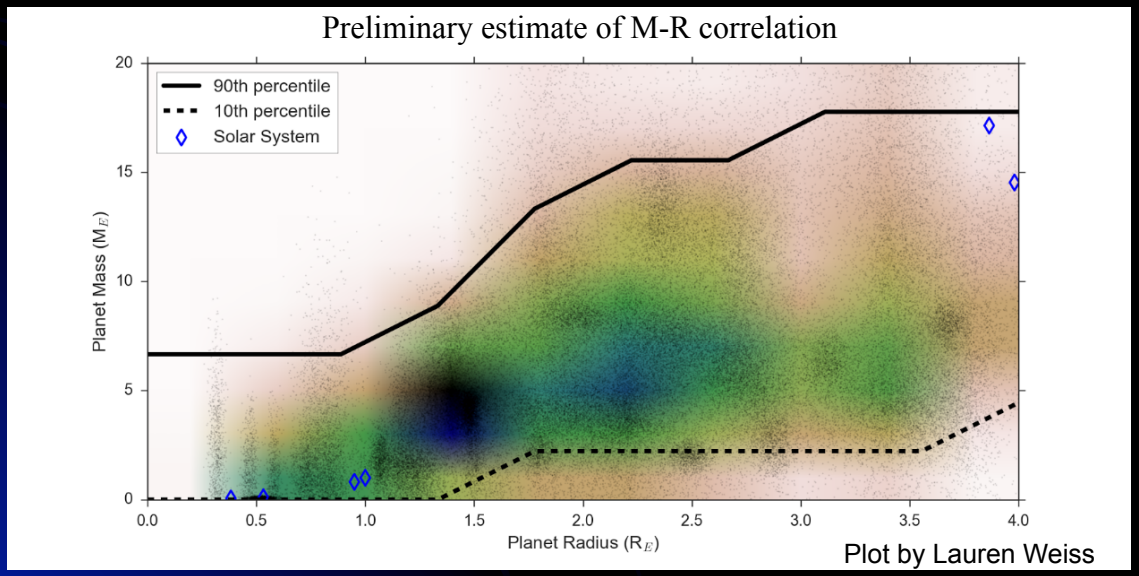


- Any estimate of eta_Earth should always very clearly specify:
  - Whether 0.5-1.0 bin is included or not
  - What extrapolation assumpsion was made
- Many discrepancies in eta_Earth estimates can be traced to inclusion or exclusion of 0.5-1.0 bin
- Mission study teams may want to consider the possibility of a large number of potentially habitable planets in the 0.5-1.0 bin

New focus group: Mass-Radius relationship

led by Angie Wolfgang and Lauren Weiss





- Purpose: enable SAG13 occurrence rate submissions based on RV planets
- M-R relationship is fundamentally not a 1-1 map (e.g. M = f(R)), but a correlation (e.g. density function C(M,R))
- M-R focus group deliverables
  - an estimate of this correlation based on open community input
  - analysis of uncertainties and dependency on period and other parameters
- Notes about plots / methods
  - TTV data is included
  - Black dots: MC posterior simulation accounting for uncertainties on currently known M-R planets
  - Color map: estimate of the 2D correlation density function (using Gaussian kernel density estimator)

Conclusions

- Completed products
  - Proposed conventions for binning planet periods, sizes, and star temperatures
  - Living repository of occurrence rate datasets submitted by scientists
  - Code to visualize them and compute statistics (first version done, evolving)
  - All can be found on https://drive.google.com/drive/folders/0B520NCfkP4aOQUJYdmUzQTJkdkE
- Expected products (by start of 2017)
  - More thorough analysis of submissions
  - Final 3D matrix of SAG13 bin values representing a combination of all submissions
    - With uncertainties and analysis of deviations
  - Recommendation for a standard assumption(s) of parametrized multi-variate distribution(s) for missions
    - With a discussion of uncertainties and method
    - Estimates of occurrence rates relevant to habitable planets based on this distribution
- Latest estimates of occurrences of potentially habitable planets seem to be converging (at least to a factor of ~2-3), and explanations for discrepancies are starting to clarify

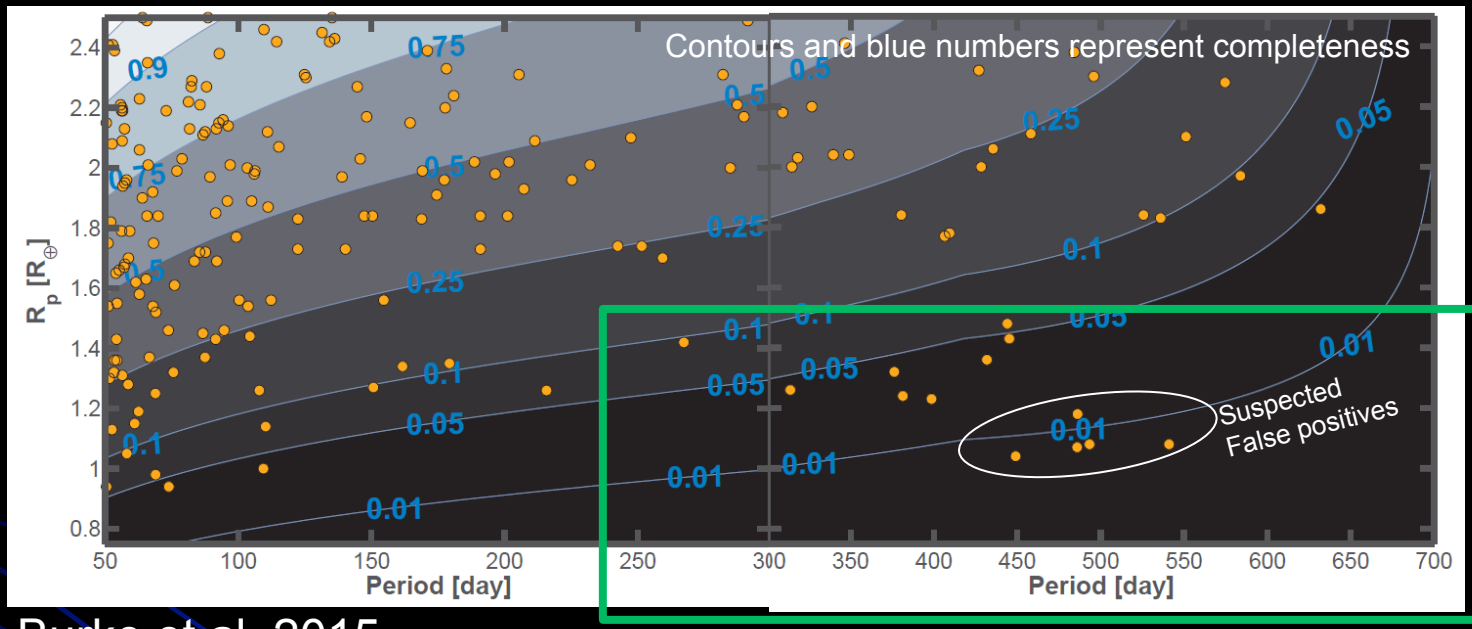
Backup slides

Extrapolation vs. using long-period candidates

[potential slide, meant to show actual planets and thus better visualize Poisson uncertainty]

Shorter periods, more reliable

Longer periods, less reliable



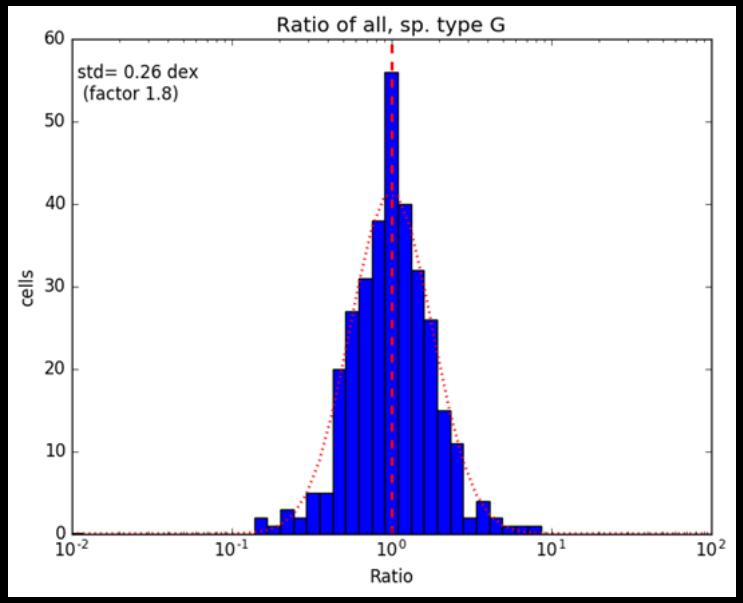
Burke et al. 2015

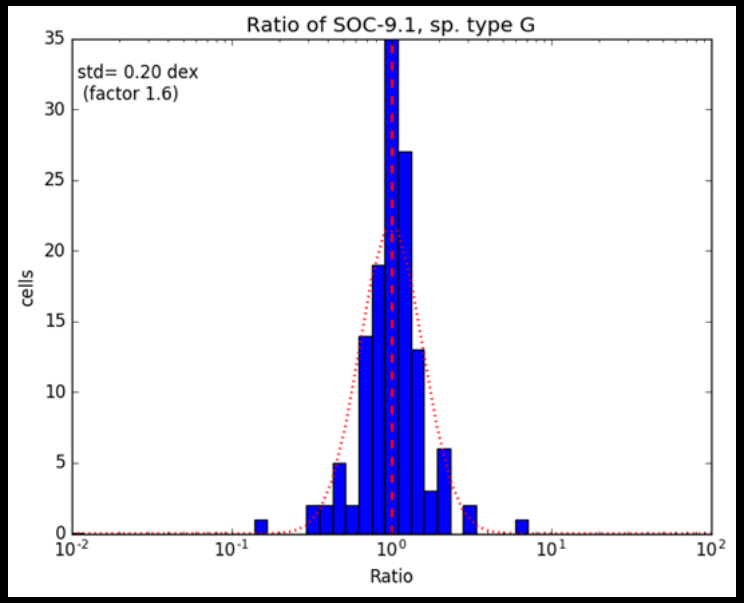
0.5-1.5 Earth size
237-860 days (Kopparapu extended HZ for Sun)

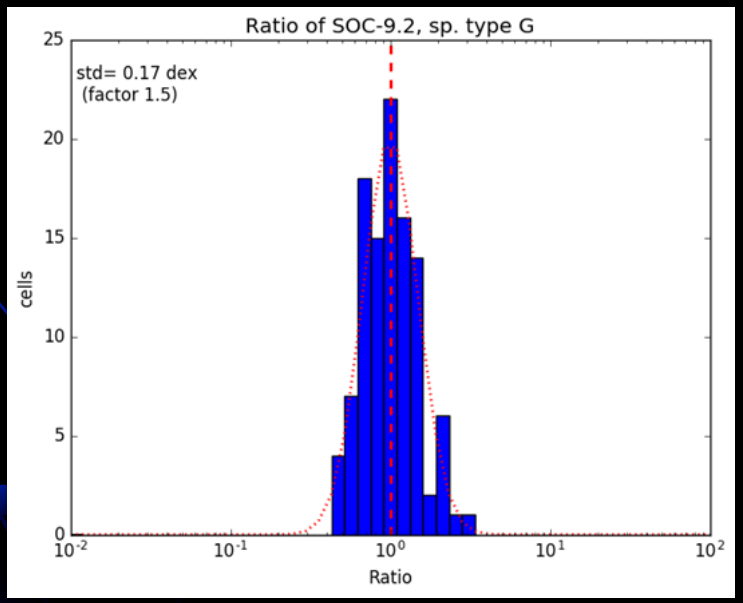
Coordination with ExEP Standards Committee

- Schedule
  - Standards team needs to have final consensus by Aug 2017
  - Standards committee product by end of 2016
  - August 2016
    - Define what the product is going to contain
- How do we extrapolate to long periods
- Mass-radius relationship
- Two versions of the green box
  - One that does not need extrapolating
  - One that does
- Pick a milestone date where the Kepler team thinks there would be no more updates

Variance in submissions







Courtesy of Gijs Mulders